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# PCM thermal storage in buildings: A state of art

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**Abstract**

A comprehensive review of various possible methods for heating and cooling in buildings are discussed in this paper. The thermal performance of various types of systems like PCM trombe wall, PCM wallboards, PCM shutters, PCM building blocks, air-based heating systems, floor heating, ceiling boards, etc., is presented in this paper. All systems have good potential for heating and cooling in building through phase change materials and also very beneficial to reduce the energy demand of the buildings.


*Keywords:* Solar energy; Phase change materials; Heating; Cooling; Building

**Contents**



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## 1. Introduction

The primary role of buildings is to protect the mankind from the extremities of climates. The entire history of shelter engineering reveals the unremitting effort of the human race to find adequate building designs to which man is best adapted. Traditional buildings, therefore, were built with considerations to climatic conditions for keeping the inside building spaces cool in summer and warm in winter. These aspects have been forgotten in the modern architecture, which essentially relies on mechanical methods of heating and cooling involving large amount of energy expense. With the growing energy crisis there is a renewed interest in those aspects of architecture, which leads to thermal comfort in buildings without (or with minimum) any expenditure of conventional energy. These aspects are termed as solar passive building concept. In addition to it, use of peak power to store the heat or coolness through thermal storage components were also picked up world wide now a days due to the incentives being provided by the electric generating companies.

The objective of this review is to present the state of art of various possible PCM-based technologies for heating and cooling the living space.

## 2. Passive building concepts

According to Sodha et al. [1] various passive heating and cooling concepts for the buildings are as follows.

### 2.1. Heating

#### 2.1.1. Increase of solar heat gain

Orientation, reflecting components, absorbing surfaces, glazing.

#### 2.1.2. Reduction of heat loss

Minimum surface to volume ratio, thermal insulation, reduction of air infiltration, wind shelter.

#### 2.1.3. Increase of internal heat gain

Living organism, condensation.

#### 2.1.4. Heat storage

Direct gain, indirect gain.

### 2.2. Cooling

#### 2.2.1. Reduction of solar and convective heat input

Orientation, shading by neighboring building, shading by vegetation, shading by overhangs textured facades, reflecting surfaces, shelter against hot winds.

#### 2.2.2. Reduction of heat transmission

Thermal insulation, air cavities.

#### 2.2.3. Increase of heat loss by radiation

Enlarged surface area, movable elements.

#### 2.2.4. Increase of heat loss by convection

Out door wind management, indoor natural ventilation, Indoor forced ventilation, Earth air tunnel flowing water.

#### 2.2.5. Increase of heat loss by evaporation

Out door and indoor air-cooling, building surface cooling.

#### 2.2.6. Heat storage

Building elements, earth cooling.

### 2.3. Heating and cooling

#### 2.3.1. Balancing temperature fluctuations

Building elements.

#### 2.3.2. Heat sources and sinks

Roof ponds, roof radiation trap, vary therm wall, earth sheltered or earth bermed structures, earth air tunnels.

For heating and cooling of the space using solar energy, the solar energy is to be collected, stored, and distributed properly in the space. In the active solar space heating/cooling system, the solar energy is collected using some kind of separate collectors. Solar energy stored in storage unit may be in sensible heat storage material, latent heat storage materials; and the energy is distributed in the space using electrically operated pumps and fans, etc. While in a passive solar heating/cooling system all the three functions of solar energy collection, storage and distribution are done by natural means and generally, no electrical or mechanical power and electronic controls are used. In the passive heating/cooling system, various elements of the buildings like walls, roof, windows partitions, etc., are so selected and so architecturally integrated that they participate in the collection, storage, transportation and distribution of thermal energy. Both, the building elements such as construction materials-like stone, bricks, concrete, water, insulation, glazing, shading, reflectors, etc., and various thermal processes such as thermal radiation, natural and forced convection, conduction air stratification, evaporation, thermo-siphoning, etc., are combined in various ways in passive designs depending on the particular need, which also depends on the site, climate and on activity. The designer or architect, if aware of different building elements and thermal process, can take decision for each particular design project. The building materials, like brick, stone concrete, phase change materials (PCMs), water, etc., form the building envelope but if these materials are heavier (thick, walls, roofs, etc.) then they may store sufficient energy and may help in time delay and lowering the heat wave amplitude. During daytime, the excess heat may be stored in these materials, which may be released during nighttime when required.

The storage systems for passive heating include: (i) direct gain and (ii) indirect gain. In direct gain concept, the heat is received through a window or a wall or glass, facing south to heat the walls, floor and objects in the room through sunlight. The area of the house thus heated tends to get very hot in the day unless storage mass is provided in the room. The fluctuations in the room are usually higher than tolerated by man for the designed, comfort level. Another effective method for reducing the swing in the room temperature is to introduce a thermal storage wall between direct solar radiation and the living place. The concept is called indirect gain. Passive heating concepts used for indirect gain are: (a) trombe wall, (b) water wall, (c) trans wall, and (d) Solarium. The storage systems for passive heating and cooling of buildings practiced are vary therm wall, earth sheltered/bermed structures, earth air tunnels, etc.

Presently, the storage for heating and cooling of the building/space is mainly based on sensible heat storage materials. Another type of thermal storage system, which were tried for heating, and cooling of buildings, is based on the concept of latent heat storage through PCMs. Unlike sensible storage materials, such as water, masonry or rocks, PCM stores much more heat per unit volume and another key advantage with the use of a PCM is that

heat storage and its recovery occurs isothermally, which makes them ideal for space heating/cooling applications.

## 3. PCMs for space heating and cooling

PCMs are "latent" heat storage materials. They use chemical bonds to store and release the heat. The thermal energy transfer occurs when a material changes from solid to liquid, or liquid to solid. This is called a change in state or phase. PCMs, having melting temperature between 20 and 32 °C, were used/recommended for thermal storage in conjunction with both passive storage and active solar storage for heating and cooling in buildings. A large number of PCMs are known to melt with a heat of fusion in the required range. However, for their employment as latent heat storage materials these materials must exhibit certain desirable thermodynamic, kinetic and chemical properties. Moreover, economic consideration and easy availability of these materials has to be kept in mind.

### *3.1. Properties of PCMs*

The PCM to be used in the design of thermal storage system should posses desirable thermophysical, kinetic and chemical properties, which are recommended as follows [2].

#### *3.1.1. Thermophysical properties*

(i) Melting temperature in the desired operating temperature range.
(ii) High latent heat of fusion per unit volume so that the required volume of the container to store a given amount of energy is less.
(iii) High specific heat to provide additional significant sensible heat storage.
(iv) High thermal conductivity of both solid and liquid phases to assist the charging and discharging energy of the storage system.
(v) Small volume change on phase transformation and small vapor pressure at operating temperature to reduce the containment problem.
(vi) Congruent melting of the phase change material for a constant storage capacity of the material with each freezing/melting cycle.

#### *3.1.2. Kinetic properties*

(i) High nucleation rate to avoid super cooling of the liquid phase.
(ii) High rate of crystal growth, so that the system can meet demand of heat recovery from the storage system.

#### *3.1.3. Chemical properties*

(i) Complete reversible freeze/melt cycle.
(ii) No degradation after a large number of freeze/melt cycle.
(iii) No corrosiveness to the construction materials.
(iv) Non-toxic, non-flammable and non-explosive material for safety.

### 3.2. Classification of PCMs

PCMs are categorized as Organic, Inorganic and Eutectic materials.

#### 3.2.1. Organic PCMs

Organic materials are further described as paraffin and non-paraffins. Organic materials include congruent melting, self-nucleation and usually non-corrosiveness to the container material. Commonly used organic PCMs for heating and cooling in buildings falling in the range of 20–32 °C with their melting point and latent heat of fusion are listed in Table 1.

#### 3.2.2. Inorganic PCMs

Inorganic materials are further classified as salt hydrate and metallics. Inorganic compounds have a high latent heat per unit mass and volumes are low in cost in comparison to organic compounds and are non-flammable. However they suffer from decomposition and supercooling which further can affect their phase change properties. The commonly used inorganic PCMs in the range of 20–32 °C are listed in Table 2.

#### 3.2.3. Eutectics

An eutectic is a minimum-melting composition of two or more components, each of which melts and freeze congruently forming a mixture of the component crystals during

Table 1
Organic substances with potential use as PCM

| Compound | Melting point (°C) | Heat of fusion (kJ/kg) | References |
|---|---|---|---|
| Butyl stearate | 19 | 140 | [21] |
| Paraffin $C_{16}$–$C_{18}$ | 20–22 | 152 | [62] |
| Capric–Lauric acid | 21 | 143 | [21] |
| Dimethyl sabacate | 21 | 120 | [66] |
| Polyglycol E 600 | 22 | 127.2 | [67,68] |
| Paraffin $C_{13}$–$C_{24}$ | 22–24 | 189 | [69] |
| (34% Mistiric acid + 66% Capric acid) | 24 | 147.7 | [68] |
| 1-Dodecanol | 26 | 200 | [21] |
| Paraffin $C_{18}$ (45–55%) | 28 | 244 | [69] |
| Vinyl stearate | 27–29 | 122 | [66] |
| Capric acid | 32 | 152.7 | [67,68] |

Table 2
Inorganic substances with potential use as PCM

| Compound | Melting point (°C) | Heat of fusion (kJ/kg) | References |
|---|---|---|---|
| $KF \cdot 4H_2O$ | 18.5 | 231 | [69–71] |
| $Mn(No_3)_2 \cdot 6H_2O$ | 25.8 | 125.9 | [72] |
| $CaCl_2 \cdot 6H_2O$ | 29 | 190.8 | [67,68] |
| $LiNO_3 \cdot 3H_2O$ | 30 | 296 | [70] |
| $Na_2SO_4 \cdot 10H_2O$ | 32 | 251 | [21,69,71] |

Table 3
Inorganic eutectics with potential use as PCM

| Compound | Melting temperature (°C) | Heat of fusion (kJ/kg) | References |
|---|---|---|---|
| 66.6% $CaCl_2 \cdot 6H_2O$ + 33.3% $Mgcl_2 \cdot 6H_2O$ | 25 | 127 | [70] |
| 48% $CaCl_2$ + 4.3% NaCl + 0.4% KCl + 47.3% $H_2O$ | 26.8 | 188 | [69] |
| 47% $Ca(NO_3)_2 \cdot 4H_2O$ + 53% $Mg(NO_3)_2 \cdot 6H_2O$ | 30 | 136 | [69] |
| 60% $Na(CH_3COO) \cdot 3H_2O$ + 40% $CO(NH_2)_2$ | 30 | 200.5 | [73] |

Table 4
Commercial PCMs available in the International market

| PCM name | Type of product | Melting point (°C) | Heat of fusion (kJ/kg) | Source | References |
|---|---|---|---|---|---|
| RT 20 | Paraffin | 22 | 172 | Rubitherm GmBH | [78] |
| Climsel C23 | Salt hydrate | 23 | 148 | Climator | [77] |
| ClimselC24 | Salt hydrate | 24 | 216 | Climator | [77] |
| RT 26 | Paraffin | 25 | 131 | Rubitherm GmBH | [78] |
| RT 25 | Paraffin | 26 | 232 | Rubitherm GmBH | [78] |
| STL 27 | Salt hydrate | 27 | 213 | Mitsubishi chemical | [76] |
| S27 | Salt hydrate | 27 | 207 | Cristopia | [74] |
| RT 30 | Paraffin | 28 | 206 | Rubitherm GmBH | [78] |
| RT 27 | Paraffin | 28 | 179 | Rubitherm GmBH | [78] |
| TH 29 | Salt hydrate | 29 | 188 | TEAP | [75] |
| Climsel C32 | Salt hydrate | 32 | 212 | Climator | [77] |
| RT32 | Paraffin | 31 | 130 | Rubitherm GmBH | [78] |

crystallization. Commonly used Organic–Organic, Organic–Inorganic and Inorganic–Inorganic eutectics PCMs used for building applications are listed in Table 3.

For latent heat storage commercial grade (CG) PCMs are preferred due to their large-scale availability and low cost. The thermophysical properties/behavior of CG materials in general was found to be very much different than those quoted in the literature for laboratory grade (LG) materials therefore, it becomes important to verify the melting temperature, latent heat of fusion and specific heat of CG latent heat storage materials.

A list of commercial PCMs, which can be used in the buildings for thermal storage (available in the International market) is given in Table 4.

## 4. Major applications of PCMs in buildings

### *4.1. Passive storage systems*

The application of PCMs in building can have two different goals. First, using natural heat that is solar energy for heating or night cold for cooling. Second, using manmade heat or cold sources. In any case, storage of heat or cold is necessary to match availability and demand with respect to time and also with respect to power. Basically three different ways to use PCMs for heating and cooling of buildings are:

(i) PCMs in building walls;

(ii) PCMs in other building components other than walls; and
(iii) PCMs in heat and cold storage units.

The first two are passive systems, where the heat or cold stored is automatically released when indoor or outdoor temperature rises or falls beyond the melting point. The third one is active system, where the stored heat or cold is in containment thermally separated from the building by insulation. Therefore, the heat or cold is used only on demand not automatically. Depending on where and how the PCM is integrated, PCMs with different melting points are applied. Currently, there is a lack of commercial PCMs in the lower temperature range that is between 5 and 25 °C. Especially between 15 and 20 °C available products show too low enthalpies. Most important PCMs are in the range of 22–25 °C, as almost everybody agrees that this is the range for building passive heating and cooling [3].

Various possible latent heat thermal energy storage (LHTES) devices studied for space heating and cooling are as follows.

#### *4.1.1. PCM trombe wall*

A trombe wall is a primary example of an indirect gain approach. It consists of a thick masonry wall on the south side of a house. A single or double layer of glass or plastic glazing is mounted about four inches in front of the wall's surface. Solar heat is collected in the space between the wall and the glazing. The outside surface of the wall is of black color that absorbs heat, which is then stored in the wall's mass. Heat is distributed from the trombe wall to the house over a period of several hours. When the indoor temperature falls below that of the wall's surface, heat begins to radiate into the room. Heat loss from the trombe wall can be controlled by an insulating curtain that is closed at night in the space between the glazing and the wall. Traditionaly trombe walls relay on sensible heat storage, but because of the potential for greater heat storage per unit mass, the PCM trombe wall is an attractive concept still awaiting successful implementation. A wall filled with PCM is constructed on the south-side window of a house. The wall is heated during the day by incoming solar radiation, melting the PCM. At night the heat is withdrawn to warm the house. For a given amount of heat storage, the phase change units require less space than water walls or mass trombe walls and are much lighter in weight. These are, therefore, much convenient to make use of in retrofit applications of buildings. Salt hydrates and hydrocarbons were used as PCMs in the trombe wall.

Telkes [4] proposed the inclusion of PCMs in walls, partitions, ceilings and floors to serve as temperature regulators. The PCMs have been used to replace masonry in a trombe wall. Askew [5] used a collector panel made of a thin slab of paraffin wax and mounted behind the double-glazing of the building and found that the thermal efficiencies are comparable with the conventional flat plate collectors. Farouk and Guceri [6] studied the usefulness of the PCM wall installed in a building for nighttime home heating using glauber salt mixture and SUNOCO P-116 wax. It was observed that if the PCM wall is designed properly, it eliminates some of the undesirable features of the masonry walls with comparable results. Schematic diagram of PCM trombe wall is shown in Fig. 1.

Bourdeau [7] tested two passive storage collector walls using calcium chloride hexahydrate (melting point 29 °C) as a phase change material. He concluded that an 8.1 cm PCM wall has slightly better thermal performance than a 40-cm thick masonry wall. Experimental and theoretical tests were conducted to investigate the reliability of PCMs as a trombe wall. Swet [8], Ghoneim et al. [9] and Chandra et al. [10] used sodium sulfate

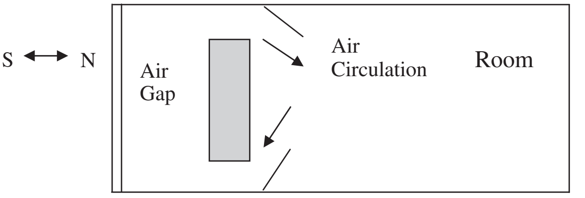



Fig. 1. Schematic diagram of PCM trombe wall.

decahydrate (melting point 32 °C) as a phase change material in south-facing trombe wall. They also reported that trombe wall with PCM of smaller thickness was more desirable in comparison to an ordinary masonry wall for providing efficient thermal energy storage (TES). Knowler [11] used CG paraffin wax with metallic additives for increasing the overall conductivity and efficiency in the trombe wall.

Buddhi and Sharma [12] measured the transmittance of solar radiation through phase change material at different temperatures and thickness. Stearic acid was used as a phase change material. They found that transmittance of the phase change material was more than the glass for the same thickness and suggested a new application of phase change material in windows/walls as a transparent insulating material.

Stritih and Novak [13] presented a solar wall for building ventilation, which absorb solar energy into black paraffin wax (melting point, 25–30 °C). The stored heat was used for heating the air for the ventilation of the house. The efficiency of the absorption was found to be 79%. The result of the simulation showed that the panel dictates the amount of stored heat as sensible or latent and that the melting point of the PCM has an influence on the output air temperature. The analysis for the heating season gave the optimum thickness of 50 mm and the melting point a few degrees above the room temperature.

### 4.1.2. *PCM wallboards*

The wallboards are cheap and widely used in a variety of applications, making them very suitable for PCM encapsulation. However, the principles of latent heat storage can be applied to any appropriate building materials. Kedl and Stovall [14] and Salyer and Sircar [15] used paraffin wax impregnated wallboard for passive solar application. The immersion process for filling the wallboards with wax was successfully scaled up from small samples to full size sheets. Processes where by this PCM could be incorporated into plasterboard either by post-manufacturing imbibing of liquid PCM into the pore space of the plasterboard or by addition in the wet stage of plasterboard manufacture were successfully demonstrated.

Shapiro et al. [16] investigated methods for impregnating gypsum wallboard and other architectural materials with PCM. Different types of PCMs and their characteristics were described. The manufacturing techniques, thermal performance and applications of gypsum wallboard and concrete block, which were impregnated with PCMs. Shapiro [17] showed several PCMs to be suitable for introduction into gypsum wallboard with possible thermal storage applications for the Florida climate. These materials were mixtures of methyl-esters namely, methyl palmitate, methyl stearate and mixtures of short chain fatty acids (capric and lauric acids). Although these materials had relatively high latent heat capacity, the temperature ranges required in achieving the thermal storage did not fall sufficiently within the range of comfort for buildings in hot climates.

Feldman et al. [18–20] carried out extensive research on the use and stability of organic compounds for latent heat storage, including fatty acids (capric, lauric, palmitic and stearic), butyl stearate, dodecanol and polyethylene glycol 600. In addition to the studies of their properties, research was also carried out on materials, which act as PCM absorbers. Various materials were considered, including different types of concrete and gypsum. The utilization of latent heat storage over a comfortable indoor temperature range in buildings can result in an increase in the thermal storage capacity in the range of 10–130%. The PCM gypsum board was made by soaking conventional gypsum board in liquid butyl stearate, a PCM with phase change range of 16–20.8 °C. The PCM gypsum board contained about 25% by weight proportion of butyl stearate. Its thermal properties were measured with a differential scanning calorimeter (DSC). In another study, investigation of the thermal performance and estimation of the benefits from the application of PCM gypsum board in passive solar buildings in terms of the reduction of room overheating and energy savings was done by Hawes et al. [21].

During the 1980s, several forms of bulk encapsulated PCM were marketed for active and passive solar applications, including direct gain. However, the surface area of most encapsulated commercial PCM products was inadequate to deliver heat to the building passively after the PCM was melted by direct solar radiation. In contrast, the walls and ceilings of building offer large areas for passive heat transfer. Neeper [22] in his study concluded that gypsum wallboard impregnated with PCM could be installed in place of ordinary wallboard during new construction or rehabilitation of a building, thereby adding the regarding thermal storage for passive solar heating as well as creating opportunity for ventilate cooling and time-shifting of mechanical cooling loads. Little or no additional cost would be incurred for installation of PCM wallboard in place of ordinary wallboard. Neeper [23] found that the thermal storage provided by PCM wallboard would be sufficient to enable a large solar heating fraction with direct gain. Neeper [24] examined the thermal dynamics of a gypsum wallboard impregnated by fatty acids and paraffin waxes as PCMs subjected to the diurnal variation of room temperature but not directly illuminated by the sun. The melting temperatures of these PCMs were adjusted by using mixture of ingredients. He examined three parameters of PCMs wall boards that may influence the energy that can be passively absorbed and released during a daily cycle: (a) the melt temperature of the PCM; (b) the temperature range over which melt occurs; and (c) the latent capacity per unit area of wall board. Several workers investigated methods for impregnating gypsum and other PCMs [25–28]. Limited analytical studies of PCM wallboard have been conducted, but few general rules pertaining to the thermal dynamics of PCM wallboard are available.

Stovall and Tomlinson [29] examined the shifting of heating and cooling loads to off-peak times of the electric utility, but did not reach general conclusions regarding the optimal PCM properties. For wallboard heated by absorption of direct solar radiation, Drake [30] found the optimal melt temperature to be proportional to the absorbed solar energy. Peippo et al. [31] also considered heating only by direct solar radiation, and concluded that the optimal diurnal storage occurs with a melt temperature 1–3 °C above average room temperature. Stetiu and Feustel [32] presented a thermal building simulation program based on a finite difference approach to evaluate numerically the latent heat storage performance of treated PCM wallboard. Thermal mass was utilized to reduce the peak power demand and down size the cooling or heating systems. Athienitis et al. [33] conducted an extensive experimental and numerical simulation study in a full scale out

door test room with PCM gypsum board as inside wall lining. An explicit finite difference model was developed to simulate the transient heat transfer process in the walls. Their one-dimensional nonlinear numerical simulation successfully predicated the measured temperature history of the walls. Kissock et al. [34] presented the results of an experimental study on the thermal performance of wallboards imbibed to 30 wt% with commercial paraffin PCM (K18) in simple structures. The results indicated that peak temperature in the phase change test cell was up to 10 °C less than in the control test cell during sunny days.

Kalousck and Hirs [35] simulated the use of PCM wallboard in an attic house. They compared the simulated thermal comfort in two rooms in an attic house during the summer where the first room was with conventional wallboard and the second room with PCM wallboard. The PCM in the simulation was TH29 with a melting point of 29 °C, 30% in wallboard. They concluded that simulated PCM wallboard could maintain summer indoor thermal comfort in the room of the attic house and the surface temperature and the air temperature in the room decreased by 3.5 and 2.5 °C, respectively.

#### *4.1.3. PCM shutter*

In this concept, shutter-containing PCM is placed outside of window areas. During daytime they are opened to the outside the exterior side is exposed to solar radiation, heat is absorbed and PCM melts. At night we close the shutter, slide the windows and heat from the PCM radiates into the rooms. Buddhi et al. [36] studied the thermal performance of a test cell (1 m × 1 m × 1 m) with and without phase change material. CG lauric acid (melting point, 49 °C) was used as a latent heat storage material. He found that the heat storing capacity of the cell due to the presence of PCM increases up to 4 °C for 4–5 h, which was used during nighttime.

#### *4.1.4. PCM building blocks*

Building blocks or other building materials impregnated with a PCM are used in constructing a building, resulting in a structure with a large thermal inertia without the large mass associated with it. Collier and Grimmer [37] showed that a macro-encapsulated PCM material cemented within masonry building blocks results in significant increase in the system performance over an equivalent volume of concrete. Hawes et al. [38] and Hawes and Feldman [39] studied the thermal performance of PCMs (Butyl stearate, Dodecanol, Paraffin, Tetradecanol) in different types of concrete blocks. Lee et al. [40] studied and presented the results of macro-scale tests that compare the thermal storage performance of ordinary concrete blocks with those that have been impregnated with two types of PCMs, butyl stearate and commercial paraffin.

Hadjieva et al. [41] investigated the heat storage capacity and structural stability at multiple thermal cycling of the composite PCM concrete system that consists of sodium thiosulfate pentahydrate absorbed into porous. They concluded that the large absorption area of autoclaved porous concrete serves as a good supporting matrix of an incongruently melting $Na_2S_2O_3 \cdot 5H_2O$ (melting point, 48 °C) and improves its structure stability during thermal cycling. The heat capacity of the investigated PCM concrete system stays high. The working temperature range of its phase transition was about 10 °C for a PCM composite melted partially. Farid and Kong [42] constructed slabs, containing encapsulated PCM, $CaCl_2 \cdot 6H_2O$ (melting point, 29 °C) in spherical plastic nodules. The

plastic spheres contained about 10% empty space to accommodate volume expansion of the PCM during melting.

#### 4.1.5. Air-based heating system

Morrision and Abdel Khalik [43] and Jurinak and Abdel Khalik [44] studied the performance of air-based solar heating systems using phase change energy storage unit. The main objectives of their work were: (i) to determine the effect of the latent heat and melting temperature of phase change material on the air-based solar heating system and (ii) to develop empirical model of significant phase change energy storage units. They concluded that the PCM should be selected on the basis of melting point and its latent heat and also found that air-based system utilizing sodium sulfate decahydrate as a storage medium requires roughly one-fourth the storage volume of a rock bed and one-half the storage volume of a water tank. Ghonein and Klein [45] compared theoretically the performance of phase change and sensible heat storage for air- and water-based solar heating system. Schematic representation of a standard solar air space-heating system is shown in Fig. 2. Sodium sulfate decahydrate and paraffin were used as PCMs and similar results were noted as Morrision and Abdel Khalik [43].

#### 4.1.6. Floor heating

Floor is also the important part of a building and heating and cooling of buildings were tried using it. Athienities and Chen [46] investigated the transient heat transfer in floor heating systems. His study focused on the influence of the cover layer and incident solar radiation on floor temperature distribution and on energy consumption. Complete and partial (area) carpets were considered as well as hardwood cover layers over concrete or gypcrete (gypsum–concrete mixture) thermal storage. Experimental and simulation results for an outdoor test room reveal that solar beam radiation can cause a local floor surface temperature in the illuminated area 8 °C higher than that in the shaded area. Partial carpet cover further increases floor surface temperature difference up to 15 °C when solar radiation was absorbed. Solar radiation stored in the floor thermal mass was found to

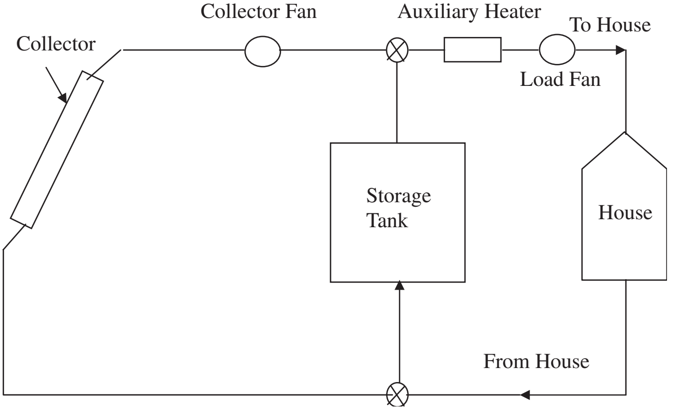



Fig. 2. Schematic representation of a standard solar air space-heating system.

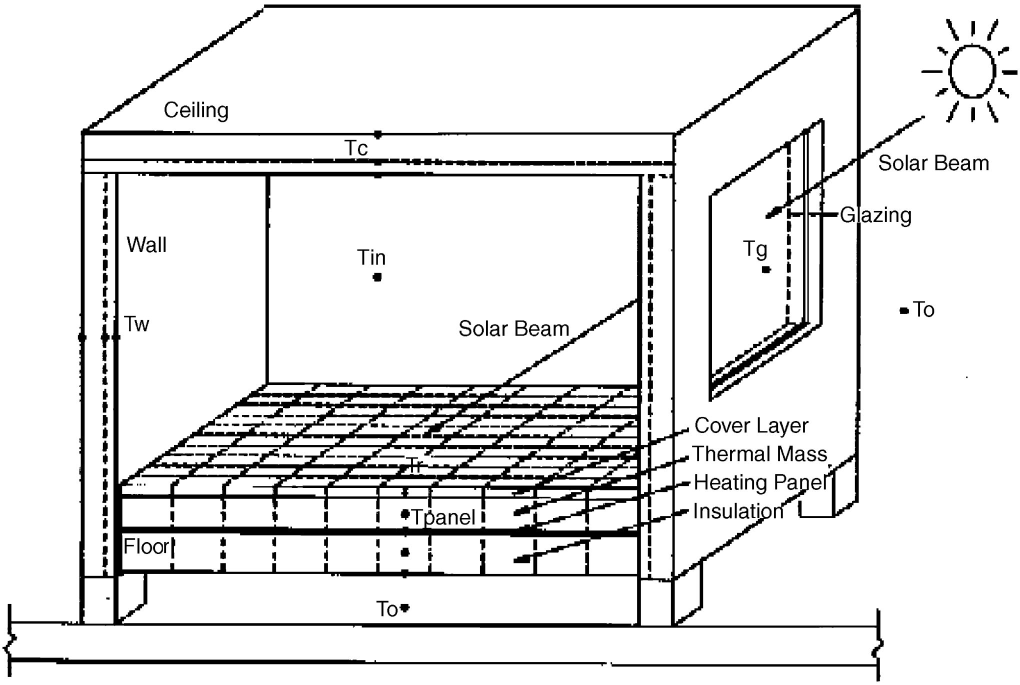



Fig. 3. Schematic representation of the test room with discretization scheme.

reduce heating energy consumption significantly (30% or more). Increase of thermal mass thickness from 5 to 10 cm did not lead to higher energy savings with conventional proportional-integral control. Advanced control algorithms need to be developed to maximize energy saving while maintaining good thermal comfort. Schematic representation of the test room with discretization scheme is given in Fig. 3.

### 4.1.7. *Ceiling boards*

Latent heat solar roof was tested in a Peruvian village to maintain near isothermal conditions in an experimental chicken brood. The brooder house was divided into two connecting parts, a patio and a heated enclosure. Two semi-circular tanks with upper face closed with glass, containing 42 kg of paraffin wax each were located below a glass roof, which was airtight. At night thick polyurethane insulators were placed between the glass roof and paraffin tanks to regulate the enclosure temperature between 22 and 30 °C [47].

A space heating system that incorporates a PCM located in the ceiling void was developed by Gutherz and Schiler [48]. Sun reflectors were used to direct the solar energy entering via the windows on to the PCMs. The main advantage of the system was that it allowed a large area to be dedicated to heat storage without the need for large volumes of storage medium that would be required with sensible heat storage. It was shown that the use of such a system has the potential to recover 17–36% of heat lost over the initial gains. Turnpenny et al. [49] developed a latent heat storage unit incorporating heat pipes embedded in phase change material. A one-dimensional mathematical model of the heat

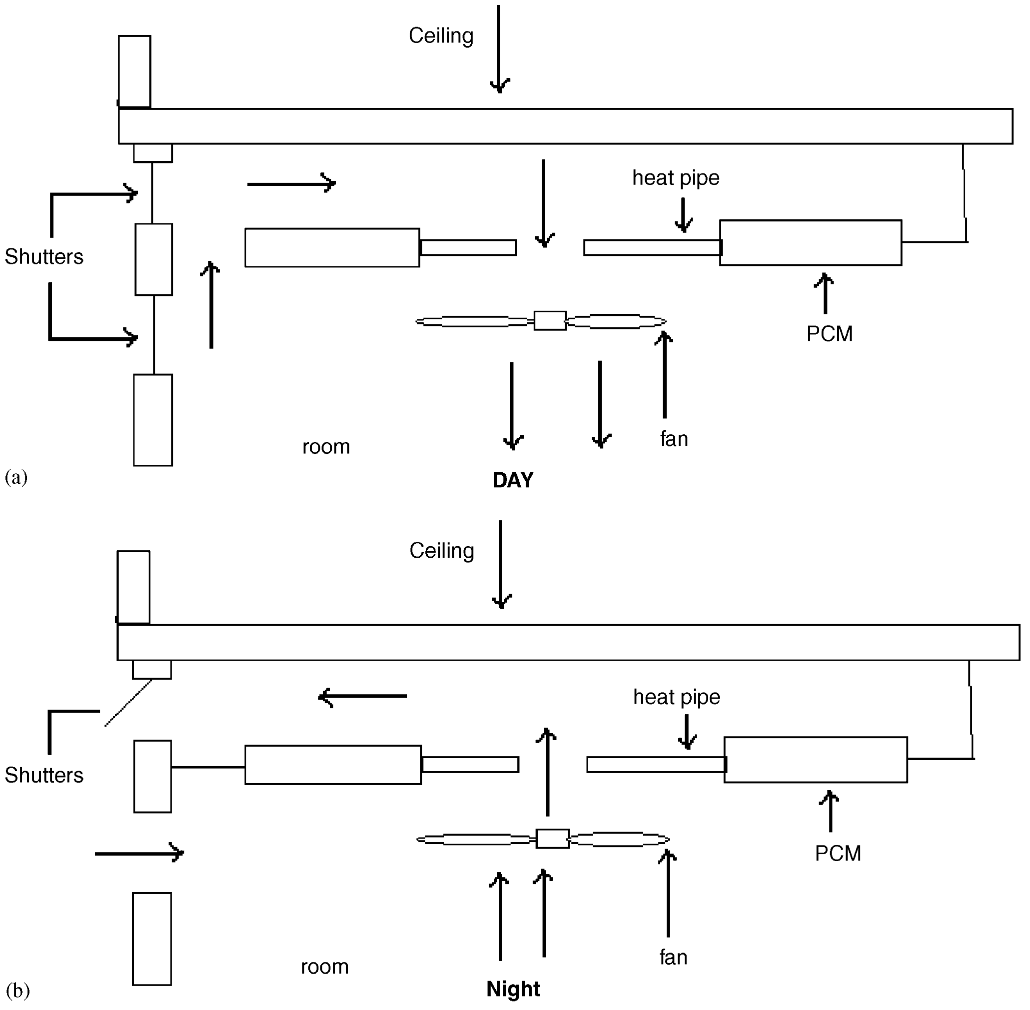



Fig. 4. Schematic diagram showing proposed heat pipe/PCM insulation system.

transfer from air to PCM was presented to allow sizing of a test unit. His system stored coolness in nighttime and released the store coolness in daytime. Schematic diagram showing proposed heat pipe/PCM insulation system is given in Fig. 4.

## 4.2. Active storage systems

### 4.2.1. Floor heating

Mostly active floor system can be used for off peak storage of thermal energy in buildings. Thus, peak loads may be reduced and shifted to nighttime when electricity costs are lower. An electrical under floor heating system having paraffin wax (melting point, 40 °C) as the PCM was proposed by Farid and Chen [50]. Sketch of the under floor heating system incorporating heat storage is shown in Fig. 5. They placed 30-mm layer of PCM

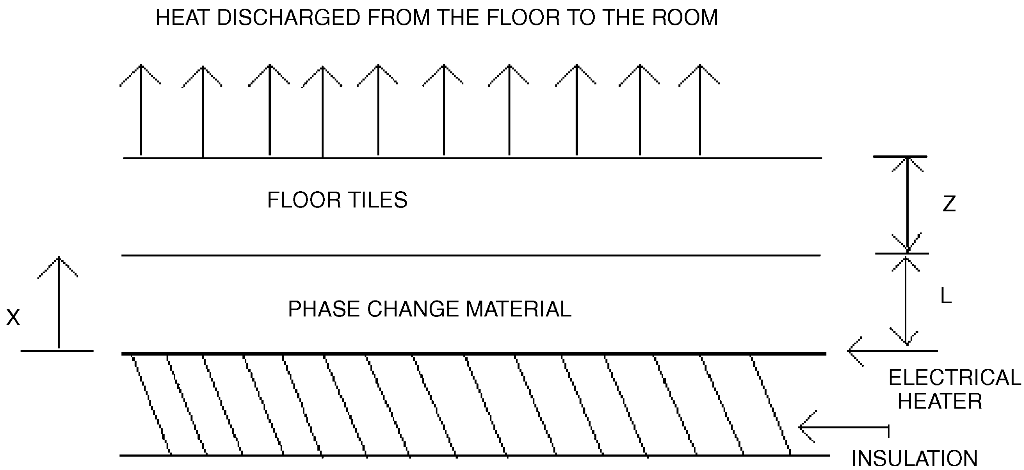



Fig. 5. Sketch of the underfloor heating system incorporating heat storage system.

between the heating surface and the floor tiles. Using computer simulation they found that the heat output of the floor could be raised significantly from 30 to 75 W/m$^2$ if PCM storage was used. Nagano et al. [51] presented a floor air conditioning system with latent heat storage in buildings. Floor size of the experimental cell was 0.5 m$^2$. Granulated phase change material was made of foamed waste glass beads and mixture of paraffin. The PCM packed bed of 3 cm thickness was installed under the floorboard with multiple small holes. The change in room temperature and the amount of stored heat were measured and results showed the possibilities of cooling load shifting by using packed granulated PCM.

Lin et al. [52] performed the experimental study of under floor electric heating system in building with shape stabilized PCM plates. They used 75 wt% paraffin as a dispersed PCM and 25 wt% polyethylene as a supporting material. The phase transition temperature and heat of fusion of paraffin were 52 °C and 200 kJ/kg, respectively. The system conclusions were:

(i) The system increased the indoor temperature without increasing the temperature difference.
(ii) The temperature of the PCM plates was kept at the phase transition temperature for a long period after heaters stopped working. More than half of the total electric heat energy was shifted from the peak period to the off-peak period, which would provide significant economic benefit by different electric tariff between day and night.
(iii) Small indoor temperature difference along vertical direction appeared because the under-floor heating could warm the indoor air uniformly. The heating system was comfortable and energy-efficient.

*4.2.2. Ceiling boards*

Ceiling boards are the important part of the roof, which are utilized for the heating and cooling in buildings. Bruno [53] developed a system, which stored coolness in phase change material in off peak time and released this energy in peak time. The effects of the peak-cut

control of air-conditioning systems using PCM for ceiling board in the building were also tried. The melting point of the PCM used was of the range 20–30 °C, which was almost equal to the room temperature suitable for the purpose. Kodo and lbamoto [54] made an effort to reduce the peak load of air conditioning system using the PCM in the ceiling board. The melting point and latent heat of fusion of used PCM was 24.5 °C and 174.4 kJ/kg, respectively. The system was basically same as the ceiling chamber system. At the cooling time, the cool air from the air-handling unit (AHU) was passed through the ceiling chamber space to store the coolness in the PCM ceiling board. The coolness was recovered during 2 h of the peak to cool the room. It was found that the rise in the room temperature was only about 2 °C as compared to the 6 °C rise in the room temperature, if PCM was not used. Schematic diagram showing outline of ceiling board system having PCM is shown in Fig. 6.

### 4.2.3. *Other systems*

Kaygusuz and Ayhan [55] investigated the performance of the combined solar heat pump system with energy storage in encapsulated phase change material packing for residential heating. They concluded that the average seasonal coefficient of performance (COP) values of the series, parallel and dual source heat pump systems for heating seasons (December–May) were 4.0, 3.0 and 3.5, respectively. The average seasonal collector efficiencies of the solar, parallel and series systems were 50%, 50% and 60%, respectively. The average seasonal storage efficiencies of the same systems were 55%, 53% and 60%, respectively. The percent of heat load met (F) by the series, parallel, dual and solar systems

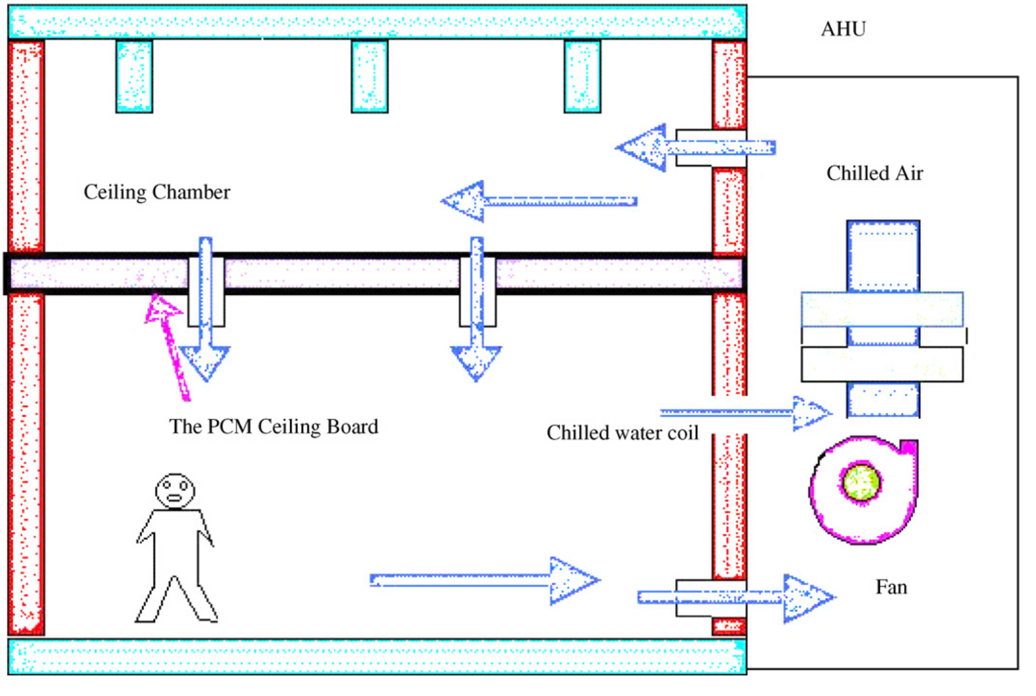



Fig. 6. Schematic diagram showing outline of ceiling board system having PCM.

were 0.60, 0.75, 0.80 and 0.25, respectively. The seasonal performance factors (SPF) of the series, parallel and dual source systems were 3.30, 3.70 and 4.20, respectively. The dual source system saved net energy of 12,056 kW per heating season, while the parallel system saved 10,120 kW and the series system saved 9390 kW energy. It was concluded that the dual source heat pump system takes advantage of the best features of the series and parallel systems.

The concept of free cooling was developed for air conditioning applications, where coolness was collected and stored from ambient air during night, and relived to the indoor ambient during the hottest hours of the day [56,57]. Vakilatojjar and Saman [58] worked on the analysis and modeling of phase change storage system for air conditioning applications. The PCMs used were $CaCl_2$ (melting point, 28 °C) and $KF \cdot 4H_2O$ (melting point, 18.5 °C). Air was used as the heat transfer fluid. The results showed that the air velocity profile at the entrance does not affect the heat transfer characteristics and the outlet air temperature considerably. Better performance was obtained by using smaller air gaps and thinner PCM slabs, however, this increased the number of PCM containers and the total volume of the storage systems and would lead to higher pressure drop across the storage system.

Another application of PCMs in buildings is thermoelectric refrigeration. Omer et al. [59] and Riffat et al. [60] integrated a phase change material in the thermal diode to improve effectiveness of the heat sink. John et al. [61] designed a novel ventilation nighttime cooling system (a novel combination of PCM and heat pipes) as an alternative to air conditioning. The system offers substantial benefits in terms of reducing or eliminating the need for air conditioning and thereby significantly reducing $CO_2$ emissions and saving energy in buildings.

Zalba et al. [62] designed and constructed an experimental unit having PCMs with melting temperature between 20 and 25 °C. The principle of the system was to store outdoor cold during night and release it indoors during day. This concept was feasible in climates where the temperature difference between day and night in summer was over 15 °C. Calmac corporation developed an active storage system for solar space heating and cooling. It employed close-spaced plastic tubing mat coiled into a spiral and inserted into a cylindrical tank containing PCM, as a heat exchanger. The system employed salt hydrate as a PCM consisting of 98% sodium thiosulfate pentahydrate and 2% sodium sulfate for space heating units and magnesium chloride hexahydrate for space cooling units. The system was successfully tested for 1000 cycles without any degradation in the performance of the system [63].

Kenneth [64] at the University of Brighton investigated and analyzed a solar space heating system that incorporated a PCM for the use in domestic buildings in the UK. The system comprised of an array of solar flat plate collectors, which delivers heated water to a storage tank and a number of PCM filled panels. PCM used was calcium chloride of melting point, 29 °C. The panels were manufactured from aluminum sheets, having length of 15 mm coiled copper tube running through them. Water heated by the solar panels was circulated through the inner pipe and the heat was transferred to the PCM contained in the outer tube, thus melting the PCM. The pipes were located under the floor and a series of fan coil units passed air over the pipes, which heated the air and this was then delivered to the space to be heated. The results showed that this system had the potential to reduce energy consumption between 18% and 32%.

Kulkarni et al. [65] studied sub-ambient phase change material, namely, benzene (melting point, 6 °C), formic acid (melting point, 7.5 °C), *N*-pentadecane (melting point, 8.5 °C) and *p*-xylene (melting point, 12 °C) and their role in TES-based space cooling application by using existing conventional chillers. The super cooling phenomenon in benzene and formic acid were found to be 1 and 6.5 °C, respectively.

## 5. Conclusion

This review paper presents the state of art of various possible PCM-based technologies for heating and cooling of buildings. Materials used by researchers as potential PCMs (lying in the range of 20–32 °C) for human comfort in buildings are described. The systems discussed in this paper have good potential for reducing the heating and cooling load in building through PCM.

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